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RXTE Observations of Cas A

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Abstract. The exciting detection by the COMPTEL instrument of the 1157 keV ^{44}Ti line from the supernova remnant Cas A sets important new constraints on supernova dynamics and nucleosynthesis. The ^{44}Ti decay also produces x-ray lines at 68 and 78 keV, whose flux should be essentially the same as that of the gamma ray line. The revised COMPTEL flux of 4×10^{-5} cm^{-2}s^{-1} is very near the sensitivity limit for line detection by the HEXTE instrument on RXTE. We report on the results from two RXTE observations — 20 ks during In Orbit Checkout in January 1996 and 200 ks in April 1996. We also find a strong continuum emission suggesting cosmic ray electron acceleration in the remnant.

INTRODUCTION

The Cas A supernova remnant is the remains of the explosion of a massive star 317 years ago (if indeed John Flamsteed observed it in 1680) at a distance of 3.4 kpc. Optical observations [1,2] suggest that Cas A is the remnant of an SNIb, or SNII from a WN Wolf-Rayet progenitor with a initial mass >25 M$_\odot$. X-ray imaging of Cas A reveals an outer, weak ring of emission assumed to be the result of the expanding shock wave interacting with the interstellar medium or wind material, and a brighter inner ring representing the reverse shock impinging upon the ejecta [3]. Spectral measurements clearly demonstrate that thermal equilibrium has not been attained and that relatively simple one- or two-temperature thermal models cannot describe the data [4]. At gamma-ray energies the detection of 1157 keV line photons [5] has provided an estimate of ^{44}Ti production in the supernova explosion which is at odds with the low apparent brightness of the supernova event [6]. As the youngest known supernova remnant, Cas A affords us the opportunity to

to study both the nucleosynthesis involved and the dynamic evolution of the forward and reverse shocks as they impinge in the interstellar medium and the slower moving material within the remnant, respectively.

Radioactive $^{44}Ti \rightarrow ^{44}Sc \rightarrow ^{44}Ca$ produced by explosive silicon burning and the freeze out from nuclear statistical equilibrium in supernovae is thought to be the primary source of galactic ^{44}Ca. The detection of gamma-ray line emission from the decay of ^{44}Ti with a mean-life of about 78 to 96 years, and its short-lived daughter ^{44}Sc, should ultimately enable us to discover the sites of the most recent supernovae in our Galaxy. These supernovae have escaped detection because of the large optical extinction by dust in the inner Galaxy, and even recent radio searches with the VLA have failed to discover any very young (<100 years old) supernova remnants in our Galaxy suggesting that they may not turn on in radio until they are older.

PREVIOUS OBSERVATIONS

The principal gamma-ray lines from the ^{44}Ti decay chain to ^{44}Sc are at 67.87 and 78.32 keV [7] with essentially equal intensities, and at 1157.0 keV 100% of the time from the much shorter lived (mean-life of 5.7 hours) ^{44}Sc. Searches for these lines by the gamma-ray spectrometers on HEAO-3 and SMM, prior to GRO, set upper limits on the line fluxes at 67.87 and 78.32 keV of 2×10^{-4} photons/cm^{2}s [8] and at 1157 keV of 8×10^{-5} to 2×10^{-4} photons/cm^{2}s, depending on Galactic longitude [9], at the 99% confidence level from any potential "point source" supernova remnant in the Galactic disk. The SMM limit of 8×10^{-5} photons/cm^{2}s from any remnant in the direction of the Galactic center also sets [9] a 90% confidence limit on the typical ^{44}Ti yield of $\leq 1.0 \times 10^{-4}$ M$_\odot$ for any class of supernovae whose frequency was greater than 1 per 100 years. Even this, however, was still consistent with the ^{44}Ti yields calculated from most current supernova models, and recent estimates of the Galactic rates of SNIa, SNIb and SNII of 1.1 h^2, 1.2 h^2 and 6.1 h^2 supernovae per 100 years, respectively. These range for SNIa from about 1.8×10^{-5} M$_\odot$ for deflagration model W7 [10] to $(0.2$ to $4.0) \times 10^{-3}$ M$_\odot$ for sub-Chandrasekhar mass models [11]; $(3$ to $8) \times 10^{-5}$ M$_\odot$ for SNIb models [12]; and $(0.14$ to $2.3) \times 10^{-4}$ M$_\odot$ for SNII for the 11 to 40 M$_\odot$ models [11].

The HEAO-3 limits together with Monte Carlo simulations of Galactic supernovae also suggest [8] a limit on the total Galactic production of ^{44}Ti of $\leq 1.0 \times 10^{-3}$ M$_\odot$ per 100 years, which is consistent with that which would be expected from the present rate of Galactic ^{56}Fe production rate of $\sim (0.8 \pm 0.6)$ M$_\odot$ per 100 years [13], if the diffuse Galactic 511 keV positron annihilation radiation comes from positrons resulting from the decay of ^{56}Ni, ^{44}Ti, and ^{26}Al, produced in supernovae. This ^{56}Fe production rate implies a corresponding Galactic ^{44}Ti production rate of $\sim (1.0 \pm 0.7) \times 10^{-3}$ M$_\odot$ per 100 years, assuming that mean Galactic mass fraction X_{44}/X_{56} has the solar value of 1.23×10^{-3}.
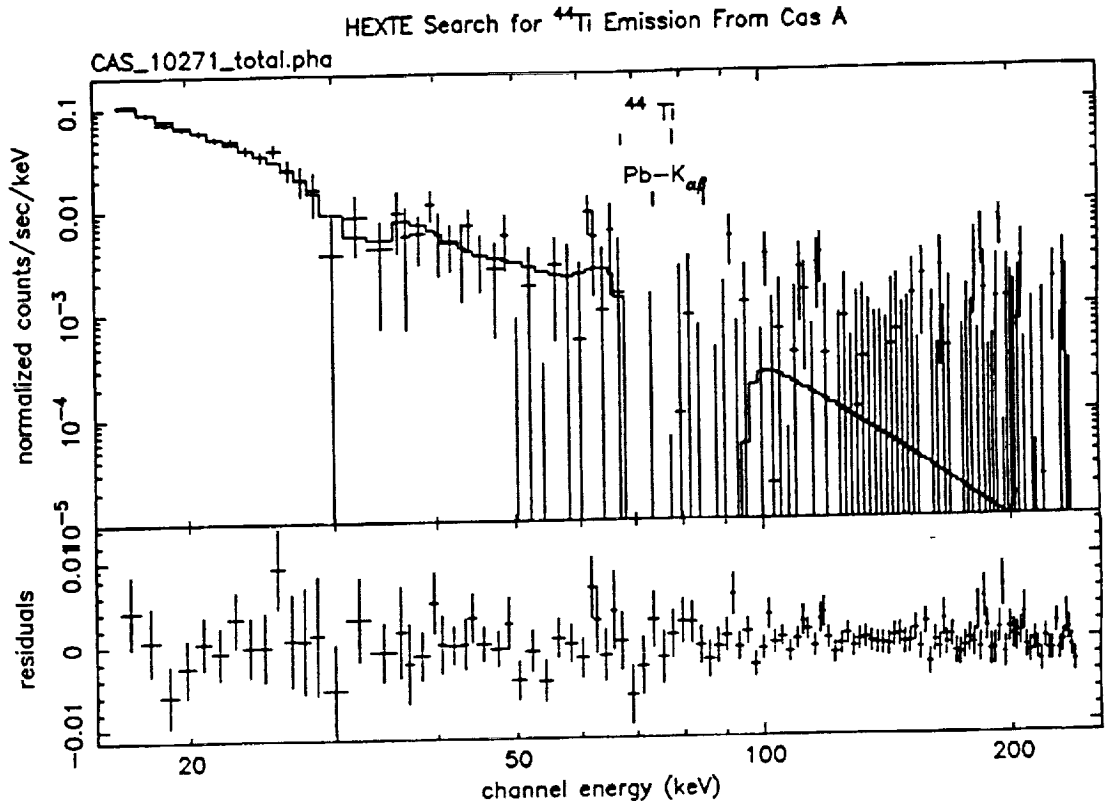
FIGURE 1. HEXTE background subtracted data for Cas A compared to best-fit model of the continuum plus ^{44}Ti lines at 67.9 and 78.3 keV. The model also includes oversubtracted $K_{\alpha\beta}$ lines of Pb from the collimator and Te and Xe from activation of Iodine. Positions of the ^{44}Ti and Pb-$K_{\alpha\beta}$ lines are shown.

The detection [14] of 1157 keV line emission from Cas A by the COMPTEL imaging gamma-ray spectrometer on GRO with a line flux of $(4.2\pm0.9)\times10^{-5}$ photons/cm^{2}s implies an initial ^{44}Ti mass of $(1.0\pm0.2)\times10^{-4}$ M$_\odot$, assuming a remnant distance of 3.4 kpc, a supernova date of 1680 A.D., and a ^{44}Ti mean-life of 96 yr. Taking the shorter mean-life of 78.2 yr would increase the initial ^{44}Ti mass by a factor of 2. Such masses are consistent or slightly higher than those that would be expected for Cas A, if it was either a massive SNIb or a SNII supernova.

The OSSE observations [15] of Cas A, searching for all three nuclear lines expected from the ^{44}Ti decay chain, yielded a best-fit of $0.40\pm^{2.26}_{2.77}\times10^{-5}$ photons/cm^{2}s for each line, with a 99% upper limit of 5.7×10^{-5} photons/cm^{2}s. The OSSE and COMPTEL results are consistent at 15% confidence for a flux of 3.5×10^{-5} photons/cm^{2}s.
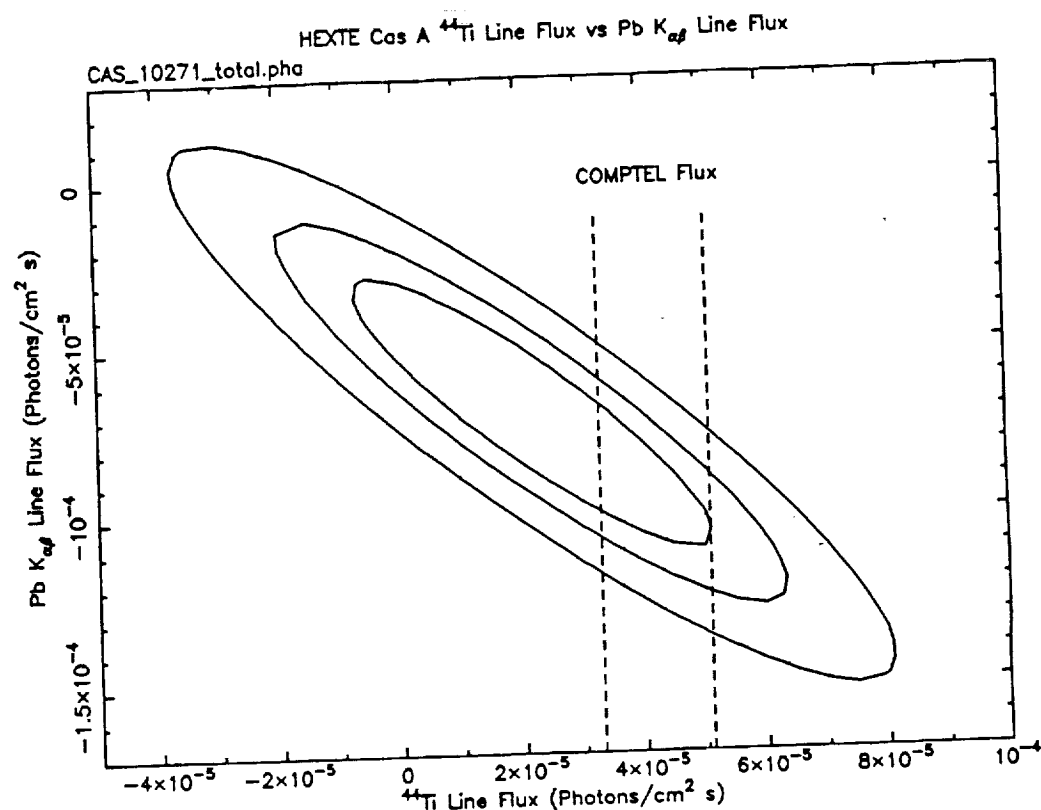
FIGURE 2. Chi-square contours (1-,2-,and 3-σ) for the line strengths of the ^{44}Ti and Pb fluorescence lines from fitting the HEXTE data. The dotted lines give the $\pm 1\sigma$ range of values from the COMPTEL analysis of the 1157 keV line.

ANALYSIS OF HEXTE OBSERVATIONS

Cas A has been observed by RXTE on two occasions: 1) during In-Orbit Checkout (IOC) on January 20, 1996 and 2) from March 31 to April 17, 1996 as our AO-1 proposal observation. The IOC observation provided 16 ks of "very clean" data, and the AO-1 observation yielded 128 ks of "very clean" data. Both data sets were fitted with a model containing a power law component plus lines at 68 and 78 keV that were constrained to have identical fluxes. The width of these lines was set at 2.5% of their energy to represent the expected Doppler broadening due to the ejecta outflow. Residuals to the fit revealed excess deviations ($\sim$1-2% of background) at the positions of the strong background lines due to fluorescence of the Pb collimators (74.2 and 85.4 keV) and to a lesser extent at 30 keV due to activation of Iodine. Thus, a simultaneous fit was performed that included the ^{44}Ti lines, the Pb lines, the 30 keV line, and a power law continuum. Figure 1 shows the result of this fit to the AO-1 observation.

Both observations yielded consistent power law indices ($\Gamma = 3.21 \pm 0.13$). The power law component may be an indication of synchrotron emission,

suggesting that cosmic ray electron acceleration is taking place in Cas A at energies in excess of 10^{13} eV [4]. Figure 2 displays the χ^2 contours for the joint variation of the ^{44}Ti lines and the lead lines for the AO-1 observation. The best fit flux for the ^{44}Ti lines is $(2.19\pm1.95)\times10^{-5}$photons/cm^{2}s. A similar analysis of the IOC data with 12.5% of the AO-1 livetime has a best fit flux of $(0.27\pm3.36)\times10^{-5}$ photons/cm^{2}s. These translate into 99% upper limits of $\leq8.0\times10^{-5}$ photons/cm^{2}s and $\leq10.3\times10^{-5}$ photons/cm^{2}s for the AO-1 and IOC observations, respectively.

CONCLUSIONS

The RXTE observations of Cas A have detected a power law component that dominates the flux above 10 keV and may be due to synchrotron emission. This in turn may be a direct indication that cosmic ray acceleration is taking place in Cas A at high energies. The 67.9 and 78.4 keV lines from ^{44}Ti decay are marginally consistent with that seen by COMPTEL for the 1157 keV line from the subsequent decay of ^{44}Sc and the OSSE 99% confidence upper limits. We are currently analyzing the second 200 ks observation of Cas A by RXTE during the AO-2 cycle.

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